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HURRICANE STUDIES OF NEW YORK HARBOR

By Samuel Gofseyeff[1] and Frank L. Panuzio,[2] F. ASCE

With discussion by Messrs. D. M. Thomas; Basil W. Wilson; and Samuel Gofseyeff and Frank L. Panuzio

SYNOPSIS

A description is given of the New York Harbor hurricane studies undertaken by the New York District, Corps of Engineers, under authority of Public Law 71, 84th Congress.

Results are presented of a historical study of hurricanes and other tropical and extratropical storms, including frequency of occurrence, maximum experienced tide elevations and storm surge heights, storm tide frequency, and other storm effects.

For the September 1938 and September 1944 hurricanes, as well as for a maximum probable hurricane, predicted storm surge heights are given and transposed to a critical track east of New York City. The respective values of approximately 9 ft, 12 ft, and 15 ft at the mouth of New York Bay were computed from a formula derived from an empirical and theoretical study that correlated storm surges with meteorological conditions of past storms.

Data are included on estimated damages, hazards, and effects of tidal inundation to 15 ft above mean sea level. If high storm surges such as were experienced during the 1821 hurricane occurred coincident with high tide, the predicted probable hurricane tides would produce inundation up to 15 ft above mean sea level. A damage appraisal disclosed that primary physical and nonphysical damages in the New York Harbor area might reach five billion dollars

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1 Chf., Beach Erosion and Hurricane Reports Sect., Corps of Engrs., U.S. Army Engr. Dist., New York, N. Y.

2 Asst. Chf. for Civ. Works, Engrg. Div., Corps of Engrs., U. S. Army Engr. Dist., New York.

from such a flood. Secondary effects would be calamitous, and virtually all economic activity in the area would cease.

Possible remedial measures, including barriers, levees, and flood walls, are presented. The cooperation of Federal, state, municipal, and other interests in the New York Harbor hurricane study is described.

GENERAL

Authority for Hurricane Studies.—Although the problem of hurricanes has existed for many centuries, an upsurge of Federal interest in this problem be-

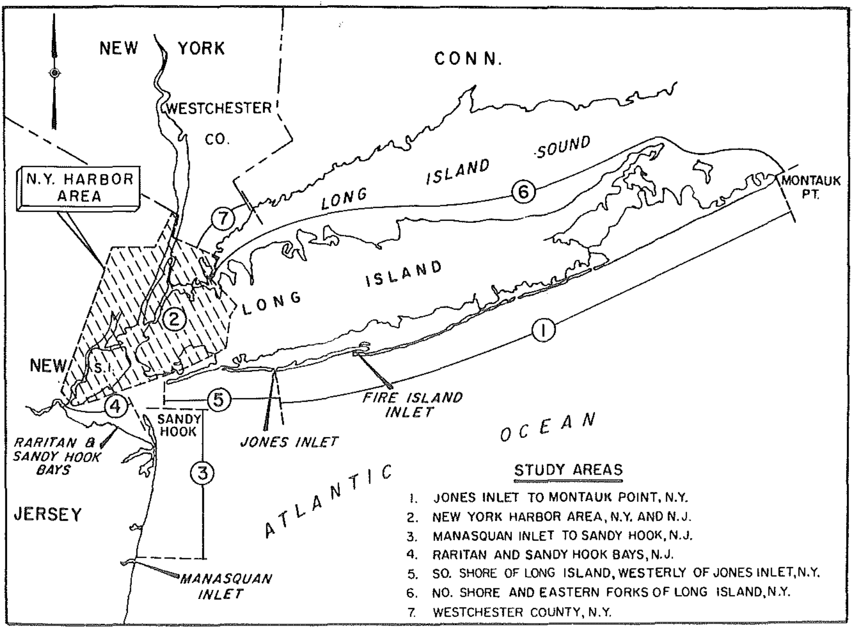

FIG. 1.—AREAS OF AUTHORIZED HURRICANE STUDIES IN NEW YORK DISTRICT

gan in 1955, after the destructive hurricanes of 1954 that caused severe property damage and loss of life in the Northeast.

On June 15, 1955, Congress authorized a hurricane study of the eastern and southern seaboard of the United States to be made under the direction of the Chief of Engineers, in cooperation with the Department of Commerce, mainly the Weather Bureau (USWB), and other Federal agencies concerned with hurricanes.[3] It specified that the survey should include the securing of data on the behavior and frequency of hurricanes, determination of methods of forecasting

[3] Public Law 71, 84th Congress, 1st Session, June 15, 1955.

their paths and improving warning services, and possible means of preventing loss of life and damage to property, with due consideration for the economics of proposed breakwaters, seawalls, dikes, dams, and other structures, warning services, or other measures that might be required.

Hurricane Studies and Projects Throughout the United States.—Pursuant to the aforementioned authority,[3] hurricane studies have been completed for a number of localities along the eastern and southern seaboard of the United States. Congress has already (as of 1961) authorized seven projects for protection against tidal inundation. Four of these projects are in New England, one in New York, one in Texas, and one in Hawaii. The four New England projects are as follows: Narragansett Bay area, R. I. and Mass.;[4,5] New Bedford, Fairhaven, and Acushnet, Mass.; Stamford, Conn.; and Pawcatuck, Conn. The Texas project, at Texas City, and the Hawaii project, at Hilo Harbor, resulted from studies made under authorities other than Public Law 71.

Hurricane Studies and Projects in New York District.—The location of the authorized project in New York, covering the Atlantic Coast of Long Island from Fire Island Inlet to Montauk Point,[6] as well as the other areas in the New York District of the Corps of Engineers where studies have not been completed (as of January 1, 1962), including the New York Harbor area, is shown in Fig. 1.

HISTORICAL STUDY OF HURRICANES

General.—A review was made of historical data on hurricanes, including those data developed by the USWB,[7] by the New England Division, Corps of Engineers, by Ivan Ray Tannehill,[8] and by Gordon E. Dunn and Banner I. Miller.[9] In addition, old newspapers and other sources of information on past storms were studied in order to determine the occurrence, frequency, tidal inundation, and damage of past hurricanes that affected the New York Harbor area.

Hurricanes That Affected the New York Harbor Area.

Major Storms.—Thirty severe and unusually severe storms are known to have occurred in the New York Harbor area since 1635. The dates and classification of these storms are given in Table 1. The two storms that generally caused the highest tide levels in the harbor, namely the hurricanes of September 3, 1821, and September 12, 1960, will be described.

Hurricane of September 3, 1821.—The hurricane of September 3, 1821, caused the highest storm surge on record in the harbor. Intensive historical research was conducted by Abraham S. Kussman, storm swell specialist of the New York Office, USWB, with a view to determining the maximum height of the surge.[10]

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4 "Hurricane Protection Planning in New England," by John B. McAleer and George E. Townsend, Proc. Paper No. 1726, ASCE, Vol. 84, No. HY 4, August, 1958.

5 "Hurricane Protection in New England," by John B. McAleer and Peter J. A. Scott, Journal, BSCE, Vol. 45, No. 2, April, 1958.

6 "South Shore of Long Island from Fire Island Inlet to Montauk Point, New York," House Document No. 425, Beach Erosion Control Study and Hurricane Survey, 86th Congress, 2nd Session, 1960.

7 "North Atlantic Tropical Cyclones," Technical Paper No. 36, U. S. Weather Bur., Washington, D. C., 1959.

8 "Hurricanes," by Ivan Ray Tannehill, Princeton Univ. Press, 1956.

9 "Atlantic Hurricanes," by Gordon E. Dunn and Banner I. Miller, Louisiana State Univ. Press, 1960.

10 "Report on Hurricane of September 3, 1821," by Abraham S. Kussman, U. S. Weather Bur., New York Office, October, 1957, (unpublished).

On the basis of old street maps, records of tide levels, and newspaper accounts, which reported that the water overflowed the wharves to a height of 12 in. to 20 in. at the time of predicted low tide, Kussman estimated that the storm surge was 10 ft to 11 ft above normal. Because this surge occurred at the time of predicted low tide and when sea level may have been as much as a foot lower than it is now, Kussman concluded that recurrence of such a hurricane at a time of predicted high tide would possibly raise the water surface in New York Harbor to 15 ft above present mean sea level.

TABLE 1.—MAJOR STORMS IN NEW YORK HARBOR AREA SINCE 1635

Date (1)	Type (2)	Category (3)
August 15, 1635	Hurricane	Severe
August 3, 1638	Hurricane	Severe
August 29, 1667	Unknown	Unusually severe
May 22, 1720	Unknown	Severe
July 29, 1723	Unknown	Unusually severe
January 23, 1781	Unknown	Severe
August 19, 1788	Hurricane	Unusually severe
December 23-24, 1811	Unknown	Severe
September 22-23, 1815	Hurricane	Severe
September 3, 1821	Hurricane	Unusually severe
March 11-14, 1888	Extratropical	Severe
September 10-12, 1889	Hurricane	Severe
August 23-24, 1893	Hurricane	Severe
October 12, 1896	Hurricane	Severe
October 24-25, 1897	Extratropical	Severe
November 24, 1901	Extratropical	Severe
September 16, 1903	Hurricane	Severe
October 8-11, 1903	Extratropical and hurricane combined	Severe
December 7, 1914	Extratropical	Severe
February 5, 1920	Extratropical	Severe
February 20, 1927	Extratropical	Severe
November 9-10, 1932	Extratropical	Severe
November 17, 1935	Extratropical	Severe
September 21, 1938	Hurricane	Severe
September 14, 1944	Hurricane	Severe
November 25, 1950	Extratropical	Unusually severe
November 6-7, 1953	Extratropical	Severe
August 31, 1954 (Carol)	Hurricane	Severe
October 14-15, 1955	Extratropical	Severe
September 12, 1960 (Donna)	Hurricane	Unusually severe

The experts from old newspapers, letters, and statements that accompany Kussman's report[10] indicate that the damage during this hurricane was widespread. Most of the cellars in the lower parts of the city were flooded, causing considerable property damage, and great losses were sustained by the wharves, merchandise, and ships in the harbor.

The characteristics of the 1821 hurricane have been computed[11] by the USWB from available historical data. The central pressure was estimated to

[11] "Parameters for Hurricane of September 3, 1821, at New York City," Memorandum HUR 7-31, Hydrometeorological Sect., U. S. Weather Bur., Washington, D. C., May, 1957 (unpublished).

have been from 28.90 in. to 29.10 in., and the radius of maximum winds from 30 to 40 nautical miles. The maximum wind was computed to be from 55 mph to 78 mph. In view of these values, it was concluded that the storm was relatively weak and moderately small, and that the fast rise of the tide (reported[12] to have been 13 ft in one hour) may be attributable to the storm path and forward speed of this hurricane, which are important factors in high storm tide occurrence in New York City. The 1821 hurricane path was estimated to have been 12 miles west of New York City.

Fig. 2 shows the path of the 1821 hurricane as well as the paths of the major hurricanes of 1938, 1944, 1954, and 1960, that struck the New York Harbor area. It may be noted that of all the known major hurricanes that affected this area, the 1821 hurricane was the only one whose center passed west of New York City. Its path was, therefore, the most critical with respect to creation of high storm surge in New York Bay.

Hurricane of September, 1960 (Donna).—The latest storm to have the greatest effect in the New York Harbor area since the September, 1821, hurricane was hurricane "Donna," that struck on September 12, 1960, with maximum winds of 70 mph and gusts of up to 100 mph. The near coincidence of the storm's passage with the time of predicted high tide in New York Bay resulted in a record tide level at the Battery (lower tip of Manhattan) of 8.4 ft above mean sea level, or a foot higher than the previous maximum height recorded during the November 1953 storm, and approximately the same or slightly higher than the estimated storm tide during the September 1821 hurricane. As previously indicated, the maximum storm surge during the 1821 hurricane occurred at the time of predicted low water and was approximately 10 ft to 11 ft. The maximum storm surge during "Donna" was only 6.3 ft. It is obvious that had the surge been of a magnitude of the 1821 hurricane, the water level at the Battery would have been approximately 4 ft higher and would have reached an elevation of over 12 ft above mean sea level. Such a flood stage would have inundated much greater areas, flooded many branches of the subway system, tremendously increased the damages, and disrupted city activities.

The damages during hurricane "Donna" in the New York Harbor area exceeded twenty million dollars. The greatest loss was sustained in the areas adjacent to the Atlantic Ocean and Upper and Lower New York Bays, and along the tidal portions of the Passaic and Hackensack Rivers and Newark Bay. Considerable residential damage occurred on Staten Island and Coney Island. On the latter, almost four hundred basement apartments were flooded. Many piers in Brooklyn along the Upper Bay were structurally damaged, and cargo losses were severe. Numerous industrial plants located on low-lying ground along the New Jersey waterways suffered flood damage. Highway and subway transportation was interrupted at numerous places.

The maximum tide and surge elevations during hurricane "Donna" are shown in Fig. 3. It is to be noted that the tide at Willets Point at the western end of Long Island Sound was only 7.5 ft above mean sea level, or a foot lower than at the Battery. This is due to the fact that the storm surge reached Willets Point at a time of lower predicted tide than at the Battery.

The record of tides during "Donna" is shown in Fig. 4. It indicates that the high storm tide at Willets Point was reached approximately 4 hr after high tide at the stations in New York Bay.

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12 "Observations on Hurricanes of West Indies and Coasts of the United States," by W. Redfield, American Journal of Science and Arts, Series 1, Vol. 20, July, 1831.

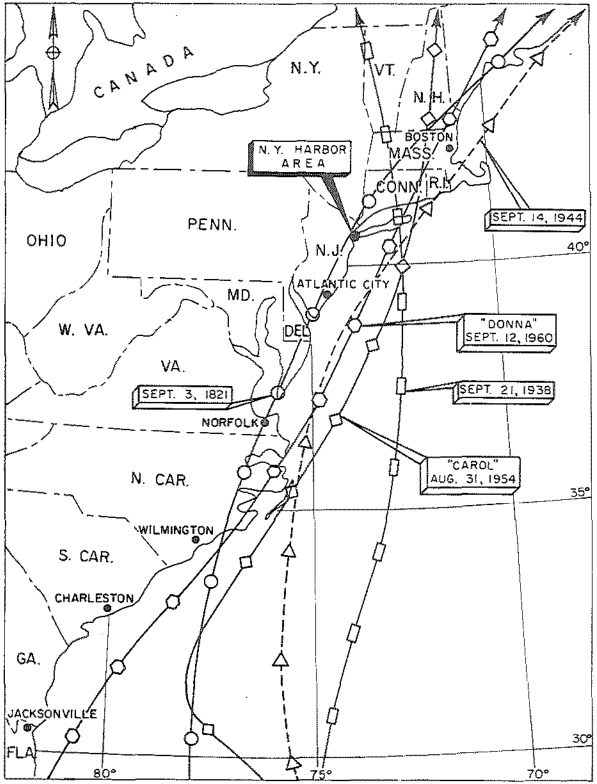

FIG. 2.—PATHS OF SEVERAL MAJOR HURRICANES

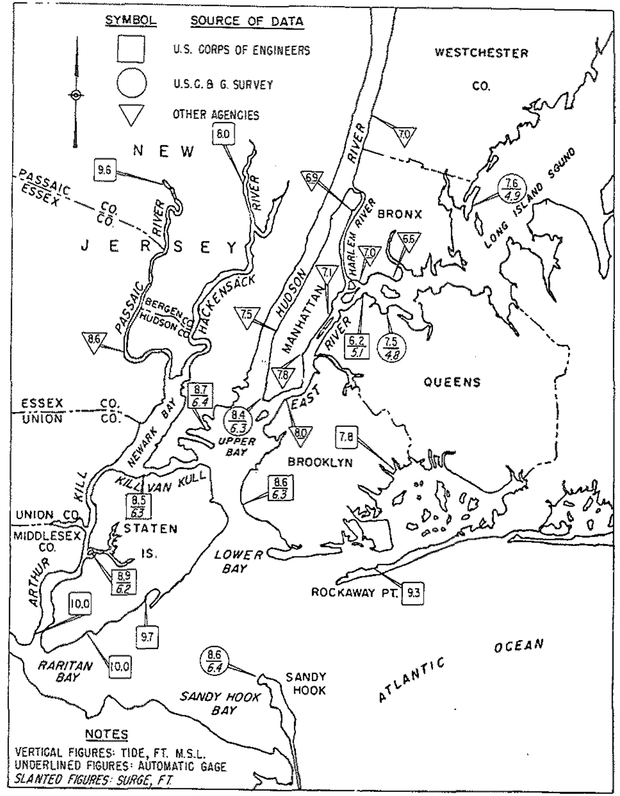

FIG. 3.—MAXIMUM TIDE AND SURGE ELEVATIONS DURING HURRICANE OF SEPTEMBER 12, 1960

Storm Frequency.—The historical study disclosed that 218 hurricanes and other tropical and extratropical storms have passed through a 200-mile wide band in the general vicinity of New York Harbor between 1635 and 1961, or one every one and a half years. Some of these storms passed outside the harbor area and either caused minor damage or only threatened the area. However, since 1900, storms have damaged or threatened this area on the average of approximately twice a year. This great difference in frequency may be partly attributed to the incompleteness of the record prior to 1900.

The total number of storms of record that either damaged or threatened the New York Harbor area, arranged by categories and centuries, is shown in Table 2. It is to be noted that the number of damaging hurricanes and other tropical

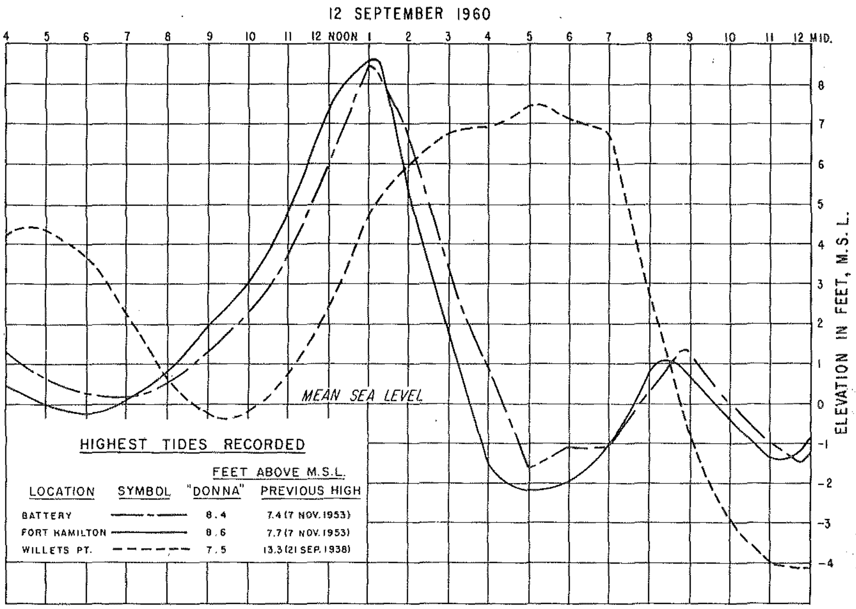

FIG. 4.—TIDE RECORD DURING HURRICANE OF SEPTEMBER 12, 1960

storms since 1900, of categories A (unusually severe), B (severe), and C (moderate), totals 25. Of these, 20 are in category C.

Because much of the data in Table 2 are not considered complete for the period of record for categories B (severe), C (moderate), and D (those that threatened the area), composite frequencies were developed using time intervals considered most representative for each category. Table 3 shows the resulting frequencies in terms of occurrences per 100 yr.

Fig. 5 shows accumulated frequencies of hurricane central pressure from 1900 to 1956, as prepared by the USWB for latitude 41° N, in the vicinity of the New York Harbor area. The frequency curve is based on hurricanes that passed through a 200-mile wide zone. Because the New York Harbor area is con-

sidered to be affected by storms passing through only a 50-mile wide portion of this zone, the frequency of hurricane central pressure for hurricanes passing in the vicinity of New York City is, therefore, approximately one-fourth of the frequency shown in Fig. 5.

Analysis of all storms between 1887 and 1961 in the New York Harbor area, including extratropical cyclones, discloses a variation in storm activity for

TABLE 2.—OCCURRENCE OF STORMS IN THE NEW YORK HARBOR AREA BY CATEGORIES FOR EACH CENTURY SINCE 1635

Category (1)	Type of Storm (2)	Time Interval (3)				
		1635 to 1700	1701 to 1800	1801 to 1900	1901 to 1961	1635 to 1961
A (Unusually severe)	Hurricane	–	1[a]	1[a]	1[a]	3[a]
	Tropical[b]	–	–	–	–	–
	Extratropical[c]	–	–	–	1[a]	1[a]
	Unknown	1	1[a]	–	–	2
	Total	1	2	1	2[a]	6
B (Severe)	Hurricane	2	–	4[a]	4[a]	10
	Tropical[b]	–	–	–	–	–
	Extratropical[c]	–	–	2	9[a,d]	11[d]
	Unknown	–	2	1	–	3
	Total	2	2	7	13[a,d]	24[d]
C (Moderate)	Hurricane	–	4	15	14[a]	33
	Tropical[b]	–	2	1	6[a]	9
	Extratropical[c]	–	–	9	28	37
	Unknown	–	3	7	–	10
	Total	–	9	32	48[a]	89
D (Threatened the area)	Hurricane	–	2	12	25[a]	39
	Tropical[b]	–	–	7	11[a]	18
	Extratropical[c]	–	–	4[d]	27[a]	31[d]
	Unknown	2	–	9	–	11
	Total	2	2	32[d]	63[a]	99[d]
TOTAL	Hurricane	2	7	32	44[a]	85
	Tropical[b]	–	2	8	17[a]	27
	Extratropical[c]	–	–	15[d]	65[a,d]	80
	Unknown	3	6	17	–	26
	Total	5	15	72[d]	126[a,d]	218

[a] These data are considered complete and were used for determination of composite storm frequency in table 2.

[b] Tropical storms which never reached hurricane intensity.

[c] Extratropical storm dates found by use of extreme high tide data since 1886 at The Battery, New York City.

[d] Includes one extratropical and hurricane combined.

various periods, as shown in Table 4. The periods of activity are in general agreement with the data prepared[7] by the USWB for the entire North Atlantic region, for the period 1886-1958. It is to be noted that since 1938, there has

TABLE 3.—COMPOSITE STORM FREQUENCY FOR THE NEW YORK HARBOR AREA

Category (1)	Type (2)	Time interval selected (inclusive) (3)	Total occurrences (4)	Frequency (occurrences per 100 yr (5)
A-Unusually severe	Tropical[a]	1701-1961	4[b]	1.5
	Extratropical	1901-1961	1	1.7
	Total			3.2
B-Severe	Tropical[a]	1801-1961	8	5.0
	Extratropical	1901-1961	9[c]	14.8
	Total			19.8
C-Moderate	Tropical[a]	1901-1961	20	32.8
	Extratropical	1901-1961	28	45.9
	Total			78.7
D-Threatened the area	Tropical[a]	1901-1961	36	59.0
	Extratropical	1901-1961	27	44.3
	Total			103.3

[a] All tropical storms including hurricanes.
[b] Includes one storm (July 29, 1723) of unknown type assumed to be tropical.
[c] Includes one storm (October 8-11, 1903) which is an extratropical and hurricane combined.

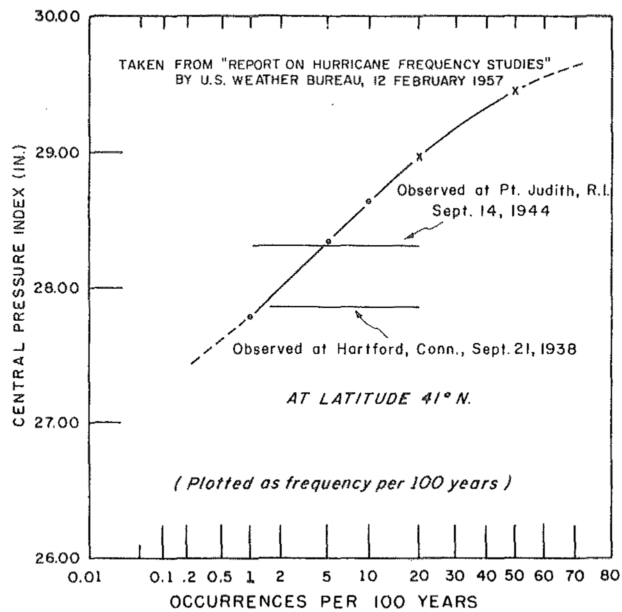

FIG. 5.—ACCUMULATED FREQUENCIES OF HURRICANE CENTRAL PRESSURE

been above average storm activity. However, Hurd C. Willett predicts,[13] by analogy between current and past climatic solar cycles, a reduced hurricane activity in this region during the next 30-yr period, up to the year 1990.

Storm occurrences by months since 1635 in the New York Harbor area are shown in Table 5. Of the total of 112 tropical storms, including those reaching hurricane intensity, 80% occurred during the months of August, September, and October. This agrees with similar data given by Dunn and Miller[9] for tropical storms in all the North Atlantic areas for the period 1887-1958. All the unusually severe hurricanes occurred during the period extending from the end of July to the end of September. Two-thirds of the unusually severe and severe extratropical storms occurred during October and November.

Maximum Experienced Tide Elevations and Storm Surges.—The maximum tide elevations and storm surges at various tide stations in New York Harbor during ten recent storms, starting with the 1938 hurricane, are given in Tables 6 and 7, respectively. The storm surge is the difference between the observed and predicted tides. It is to be noted that the September 1960 hurricane resulted in the highest tides at all the stations, with the exception of Willets Point at the western end of Long Island Sound, and ranged from 7.3 ft above mean sea level at Spuyten Duyvil, on the Hudson River at the junction with the Harlem River, to 10.0 ft at Perth Amboy, at the westerly end of Raritan Bay. Similarly, except for Willets Point, the highest surges occurred during the November 1950 storm, ranging from 7.8 ft at Spuyten Duyvil to 10.4 ft at Perth Amboy. The highest tide and surge at Willets Point occurred during the 1938 hurricane and were 13.3 ft and 9.5 ft, respectively. The lack of correlation between Willets Point and the other stations is due to the fact that tide levels there are affected by conditions in Long Island Sound, whereas the tides at the other stations are mainly influenced by the tide in New York Bay. The highest estimated surge at the Battery was from 10 ft to 11 ft during the September 1821 hurricane, as previously described.

TABLE 4.—PERIODS OF STORM ACTIVITY SINCE 1887 IN NEW YORK HARBOR AREA

Period (1)	Activity (2)	Average number of occurrences per year (3)
1887-1904	above average	2.9
1905-1930	below average	1.2
1931-1937	near average	2.0
1938-1961	above average	3.0
1887-1961	average	2.2

STORM TIDE FREQUENCY

General.—Knowledge of storm tide frequency is an important factor in the study of economic justification for remedial measures for the prevention of

[13] "A Study of the Tropical Hurricane Along the Atlantic and Gulf Coasts of the United States," by Hurd C. Willett, Inter-Regional Ins. Conf., New York, N. Y., October, 1955.

TABLE 5.—OCCURRENCES OF STORMS BY MONTHS SINCE 1635 IN NEW YORK HARBOR AREA

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
A-Unusually severe													
Tropical[a]	—	—	—	—	—	—	—	1	2	—	—	—	3
Extratropical	—	—	—	—	—	—	—	—	—	—	1	—	1
Unknown	—	—	—	—	—	—	1	1	—	—	—	—	2
Subtotal	—	—	—	—	—	—	1	2	2	—	1	—	6
B-Severe													
Tropical[a]	—	—	—	—	—	—	—	4	5	1	—	—	10
Extratropical	—	2	1	—	—	—	—	—	—	3[b]	4	1	11
Unknown	1	—	—	—	1	—	—	—	—	—	—	1	3
Subtotal	1	2	1	—	1	—	—	4	5	4	4	2	24
C-Moderate													
Tropical[a]	—	1	—	1	—	—	1	6	12	16	3	2	42
Extratropical	5	4	6	4	1	—	—	—	1	7	3	6	37
Unknown	2	1	—	—	—	—	—	—	1	4	1	1	10
Subtotal	7	6	6	5	1	—	1	6	14	27	7	9	89
D-Threatened the area													
Tropical[a]	—	—	—	—	2	6	4	16	21	7	1	—	57
Extratropical	8	6	2	2	2	—	—	1	—	3[b]	4	3	31[b]
Unknown	—	—	2	1	—	1	1	—	1	1	—	1	8[c]
Subtotal	8	6	4	3	4	7	5	17	22	11	5	4	96[c]
ALL CATEGORIES													
Tropical[a]	—	1	—	1	2	6	5	27	40	24	4	2	112
Extratropical	13	12	9	6	3	—	—	1	1	13[b]	12	10	80[b]
Unknown	3	1	2	1	1	1	2	1	2	5	1	3	23[c]
TOTAL	16	14	11	8	6	7	7	29	43	42	17	15	215[c]

[a] All tropical storms including hurricanes.
[b] Includes one extratropical storm which combined with a hurricane.
[c] Excludes three storms of unknown type, category D, for which the month is unknown.

TABLE 6.—HEIGHT OF MAXIMUM TIDE IN FEET ABOVE MEAN SEA LEVEL DURING RECENT STORMS IN NEW YORK HARBOR

Station	Sept. 21 1938	Sept. 14-15 1944	Nov. 25 1950	Nov. 7 1953	Aug. 31 1954	Sept. 11 1954	Oct. 15 1954	Aug. 12-13 1955	Oct. 14-16 1955	Sept. 12 1960	Mean high water
Fort Hamilton	6.4	6.7	7.5	7.7	5.9	4.3	5.2	4.5	6.4	8.6	2.6
Sandy Hook	5.9	7.4	7.2	7.9	6.4	4.7	4.9	4.3	6.2	8.6	2.5
Battery	6.4	6.4	7.1	7.4	5.8	4.1	4.7	4.4	6.0	8.4	2.4
Spuyten Duyvil	5.3	6.0	6.7	6.7	5.2	4.0	4.2	4.4	5.9	7.3	2.2
Perth Amboy	6.6	7.4	9.5	8.9	5.8	4.8	5.5	5.3	7.7	10.0	2.8
Willets Point	13.3	7.0	9.7	8.7	11.4	6.4	6.1	5.3	7.8	7.5	3.8

TABLE 7.—MAXIMUM STORM SURGE IN FEET DURING RECENT STORMS IN NEW YORK HARBOR

Station	Sept. 21 1938	Sept. 14-15 1944	Nov. 25 1950	Nov. 7 1953	Aug. 31 1954	Sept. 11 1954	Oct. 15 1954	Aug. 12-13 1955	Oct. 14-16 1955	Sept. 12 1960
Fort Hamilton	4.3	4.8	8.2	5.7	3.6	1.8		3.5	4.0	6.4
Sandy Hook	3.8	5.2	8.7	5.8	3.8	2.1	3.1	3.4	3.9	6.4
Battery	4.6	4.7	8.1	5.6	3.2	1.6	3.7	3.5	4.1	6.3
Spuyten Duyvil	4.1	3.7	7.8	5.8	2.9	2.0	2.9	3.2	4.2	
Perth Amboy	4.1	5.5	10.4	6.7	4.7	2.3	4.3	3.9	5.7	
Willets Point	9.5		8.1	7.4	7.3	4.0	2.8	3.1	6.0	4.8

tidal inundation. However, development of an extreme high tide frequency relationship is a difficult task. This is due to the lack of complete tide data for past storms, the difficulty of predicting the frequency of occurrence of future hurricanes and other major storms, and the uncertainty about the future rise of sea level.

Storm Tide Frequency at the Battery.

Tide Records.—The Battery in New York City has the longest period of tidal record and the best historical data of any other locality in the New York Harbor area. Tide readings at Pier A, Hudson River at the Battery, were begun in 1886 and are still being taken by the New York City Department of Marine and Aviation. Tide readings at the Battery have also been taken in the past by the Corps of Engineers, and an automatic tide gage is under operation by the Coast and Geodetic Survey, United States Department of Commerce (USC & GS). Data on these gages and other tide gages in the New York Harbor area are given in Report No. 7 of the National Hurricane Research Project.[14]

Extreme High Tide Frequency Curve.—A composite extreme high tide frequency curve developed for the Battery is shown in Fig. 6. In preparing this curve, use was made of all available tide data. Initially, two curves were drawn giving the frequency of high tides for tropical and extratropical storms. To obtain the upper part of the tropical storm curve, use was made of the hurricane central pressure frequency relationship developed by the USWB,[15] for latitude 41° N, as shown in Fig. 5; also used were the hurricane surges computed[16] by Basil W. Wilson, F. ASCE, for the New York Bay. These hurricane surges will be described later.

The results obtained from the USWB data were divided by four in order to derive the upper part of the tropical storm frequency curve. This was considered reasonable because the New York Harbor area is affected by storms passing only through an approximately 50-mile wide portion of the 200-mile wide band used by the USWB for the hurricane central pressure frequency relationship, as previously indicated. The upper part of the extratropical frequency curve was obtained by extrapolation of the computed data. The final frequency curve was obtained by adding together the frequencies for tides caused by both tropical and extratropical storms, as shown in Fig. 6. It is to be noted that elevations on the figure refer to mean sea level, which is the average condition for astronomical tide.

A comparison of the tide frequency relationship with the storm frequency developed from historical records, as previously described, indicates that the relationship is sound. The composite frequency of unusually severe storms, as given in Table 3, is 3.2 per 100 yr, denoting a 3.2% chance of occurrence. From all available data, it is usually considered reasonable to associate such storms with a tide of approximately 8 ft above mean sea level at the Battery, as occurred during the hurricane of September, 1821, and September, 1960. The chance of occurrence of a storm tide of 8 ft, as given in Fig. 6, is 3.5%.

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14 "An Index of Tide Gages and Tide Gage Records for the Atlantic and Gulf Coasts of the United States," Report No. 7, Natl. Hurricane Research Proj., U. S. Weather Bur., Washington, D. C., May, 1957.

15 "Frequency of Central Pressure Indices Along Atlantic Coast," Memorandum HUR 2-1, Hydrometeorological Sect., U. S. Weather Bur., Washington, D. C., 1957 (unpublished).

16 "The Prediction of Hurricane Storm-Tides in New York Bay," by Basil W. Wilson, Technical Memorandum No. 120, Beach Erosion Bd., Washington, D. C., August, 1960.

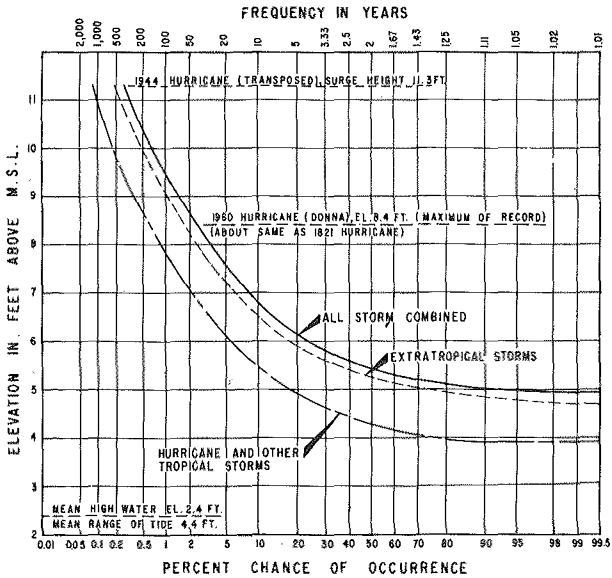

FIG. 6.—COMPOSITE EXTREME HIGH TIDE FREQUENCY FOR BATTERY

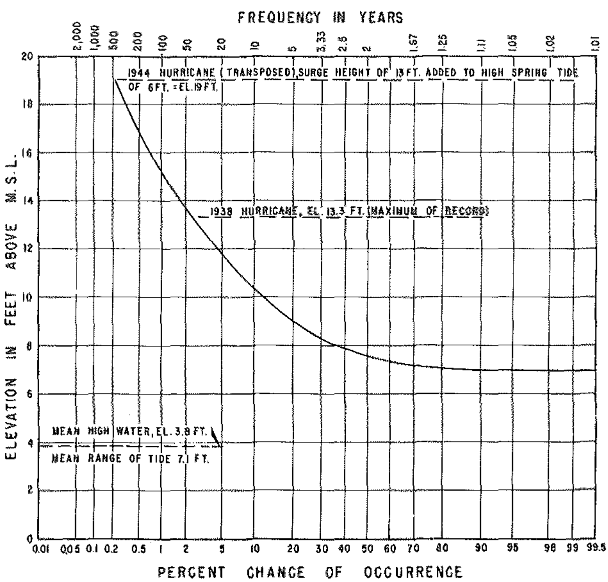

FIG. 7.—EXTREME HIGH TIDE FREQUENCY FOR WILLETS POINT

This compares well with the foregoing 3.2% chance of occurrence of unusually severe storms.

Storm Tide Frequency at Willets Point.

Tide Records.--Tide records at Willets Point at the western end of Long Island Sound are available for dates since 1931 from an automatic gage operated by the USC & GS. Tide records in this vicinity are also available from a gage operated by the Corps of Engineers at Fort Schuyler between 1920 and 1933. Both gages give a total period of record of approximately 40 yr.

Extreme High Tide Frequency Curve.—An extreme high tide frequency curve for Willets Point is shown in Fig. 7. This curve was obtained by using the available tide records and by transposition to Willets Point of the tide frequency curve developed by the New England Division, Corps of Engineers, for Stamford, Conn.,[17] 20 miles east of Willets Point. In developing the upper part of that curve, use was made of the results of computations of hurricane surge potentials in Long Island Sound, as determined by the Department of Oceanography of the Agricultural and Mechanical College of Texas, in connection with research work undertaken under contract with the Beach Erosion Board. Data were included for a design hurricane that corresponded to a transposition of the September 1944 hurricane to a path that causes the highest storm surge heights in Long Island Sound. The resulting maximum surge at Willets Point is 13 ft, which, added to a mean high tide of approximately 4 ft above mean sea level, would yield a tide elevation of 17 ft above mean sea level. This elevation is approximately 2 ft higher than a corresponding elevation at New York Bay that would result by adding to the mean high tide elevation in the bay a computed 12-ft storm surge height from a transposed September 1944 hurricane that is critical to that area.

Storm Tide Frequency at Other Localities in New York Harbor.—Although considerable tide data are available for various localities in New York Harbor,[14] they are insufficient for developing reliable storm tide frequency curves, because there is a lack of information regarding probable storm surge potentials from critical storms of greater intensity than previously experienced. However, an approximation of the tide frequency at certain localities within the harbor may be obtained by using the composite frequency curve for the Battery shown on Fig. 6 and the storm tide correlation curves shown in Fig. 8, that are based on combined data of nine past storms.

Effect of Rise of Sea Level.—Data on annual mean tide levels at Fort Hamilton in New York Bay from 1893 to 1960 indicate an average rate of rise of mean tide level (sea level) during this 68-yr period of approximately 1 ft per century. However, the rise since 1930 has been at the rate of 2 ft per century. In view of the uncertainty as to future rise of sea level, the effect of possible continued rise of sea level was not included in the tide frequency curves shown in Figs. 6 and 7.

ANALYTICAL PREDICTION OF PROBABLE HURRICANE TIDES

General.—In an effort to correlate storm surges in New York Bay with meteorological conditions of storms producing them, a report was prepared[16] in 1959 at the Agricultural and Mechanical College of Texas, by Basil W. Wilson.

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17 "Stamford, Connecticut, Hurricane Survey," U. S. Army Engr. Div., New England Corps of Engrs., Waltham, Mass. (unpublished).

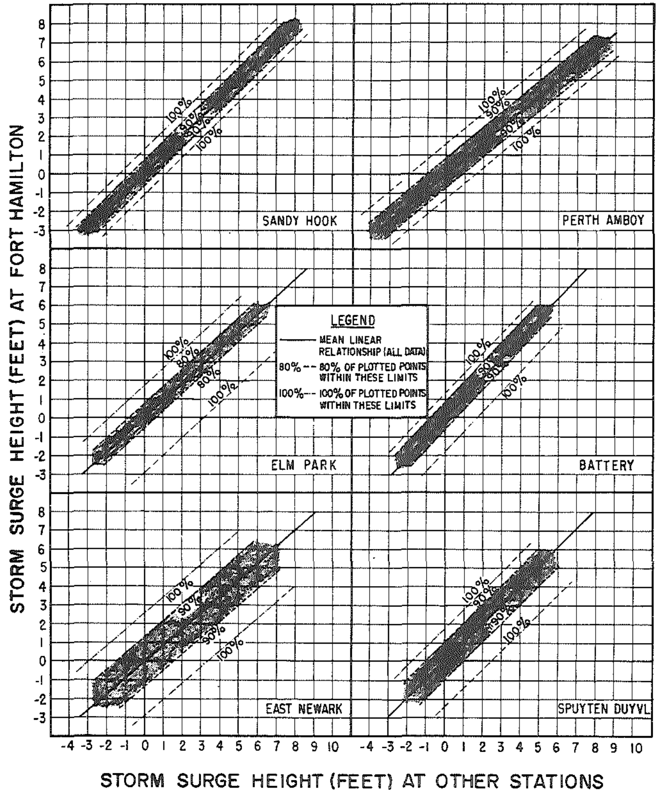

FIG. 8.—STORM TIDE CORRELATION CURVES

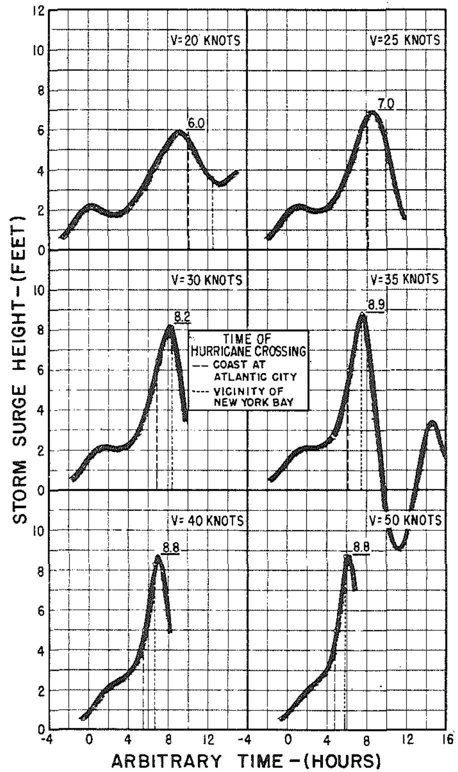

FIG. 9.—PREDICTED STORM SURGE HEIGHTS FOR HURRICANE OF SEPTEMBER 1938, TRANSPOSED

The report was included as part of the hurricane studies of the New York District of the Corps of Engineers, under a contract with the Beach Erosion Board. In the preparation of the report, use was made of all available tide and surge data for the hurricanes of September, 1938, and September, 1944, and of the extratropical storms of November, 1950, and November, 1953. Use was also made of meteorological data furnished by the USWB for these same storms,[18-21] as well as for the 1938 and 1944 hurricanes transposed to the New York Harbor area,[22,23,24] and, in addition, a maximum probable hurricane.

September 1938 Hurricane (Transposed).—The September 1938 hurricane was transposed to a new track, crossing the east coast of the United States approximately at Atlantic City, N. J., which is considered critical with respect to New York Bay. The central pressure and wind speed of this hurricane are 27.75 in. and 96 mph, respectively. The predicted storm surge heights at New York Bay for this hurricane, moving with forward speeds of 20, 25, 30, 35, 40, and 50 knots, are shown in Fig. 9. The highest surge, of approximately 9 ft, results from a speed of 35 knots. This is equivalent to the estimated forward speed of the September 1821 hurricane that caused the highest surge on record in this area.

Table 8 shows the predicted maximum storm surge heights at various localities in New York Harbor for the transposed 1938 hurricane. These data were derived by the use of curves of estimated correlation of the tides at the various localities with the tide in New York Bay at Fort Hamilton, as shown on Fig. 8. It is to be noted that for the stations furthest from Fort Hamilton the probable error in the predicted values increases as a result of the poorer correlation. Correlations were also made for other localities, including Mill Rock on the East River and Willets Point at the western end of Long Island Sound. Because the latter localities are affected by tide conditions in Long Island Sound more greatly than are localities in New York Bay, the correlations with Fort Hamilton were poor.

September 1944 Hurricane (Transposed).—The September 1944 hurricane was transposed, in a manner similar to the September 1938 hurricane, to a position critical to New York Bay. The central pressure and wind speed of this

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18 "Winds and Pressures over the Sea in the Hurricane of September, 1938," Memorandum HUR 7-8, Hydrometeorological Sect., U. S. Weather Bur., Washington, D. C., June, 1956 (unpublished).

19 "Meteorological Data over the Sea in Hurricane of September 14, 1944," Memorandum HUR 7-32, Hydrometeorological Sect., U. S. Weather Bur., Washington, D. C., August, 1957 (unpublished).

20 "Wind Speeds over the Atlantic during the Northeaster of November 25, 1950," Memorandum HUR 7-27, Hydrometeorological Sect., U. S. Weather Bur., Washington, D. C., April, 1957 (unpublished).

21 "Wind Speeds over the Atlantic Ocean during the Northeaster of November 6-7, 1953," Memorandum HUR 7-29, Hydrometeorological Sect., U. S. Weather Bur., Washington, D. C., April, 1957 (unpublished).

22 "Hurricane of September, 1938, Transposed to New York Area," Memorandum HUR 7-25, Hydrometeorological Sect., U. S. Weather Bur., Washington, D. C., February, 1957 (unpublished).

23 "Transposed Hurricane for New York Bay Studies," Memorandum HUR 7-60, Hydrometeorological Sect., U. S. Weather Bur., Washington, D. C., March, 1959 (unpublished).

24 "Transposed Hurricane for New York Bay Studies, Supplement," Memorandum HUR 7-60a, Hydrometeorological Sect., U. S. Weather Bur., Washington, D. C., April, 1959 (unpublished).

hurricane are 27.55 in. and 110 mph, respectively. The predicted storm surge heights at New York Bay for various radii, maximum winds, and various forward speeds are shown in Fig. 10. The highest surge of approximately 12 ft was computed for a hurricane having a radius of 30 nautical miles and a forward speed of 40 knots.

Maximum Probable Hurricane.—Computations were also made of a storm surge in New York Bay that would result from a maximum probable hurricane. This hurricane was assumed to have the same path and approximately the same radius and forward speed as the transposed 1944 hurricane that gave the highest surge. However, the central pressure was reduced to 27.0 in., and the wind velocities were increased by 15%, to approximately 125 mph. The resulting maximum surge of approximately 15 ft is shown in Fig. 11.

APPRAISAL OF HURRICANE DAMAGE AND HAZARD

General.—The research undertaken in connection with the hurricane problem in the New York Harbor area disclosed that a hurricane-induced tidal surge elevation of 15 ft above mean sea level could possibly occur in this area. In order to determine the hazards from tidal inundation of such an elevation to specified coastal areas within the harbor, a damage appraisal survey was made by Tippetts-Abbett-McCarthy-Stratton, consulting engineers, under contract with the New York District, Corps of Engineers.[25] The scope of work included the following:

TABLE 8.—PREDICTED MAXIMUM STORM SURGE HEIGHT AT VARIOUS LOCALITIES IN NEW YORK HARBOR FOR SEPTEMBER 1938 HURRICANE (TRANSPOSED)

Locality	Maximum Storm Surge Height	
	Surge Height, in feet	Probable Error (90% Confidence), in feet
(1)	(2)	(3)
Fort Hamilton	8.8	± 0.7
Sandy Hook	8.9	± 0.7
Battery	8.3	+ 0.6 − 0.8
Spuyten Duyvil	8.7	± 1.0
Perth Amboy	10.5	± 1.0
Elm Park	9.4	± 1.5
East Newark	10.2	± 1.6

1. A determination of the approximate extent of the inundated area;
2. an examination of dangers to life;
3. estimates of costs of primary physical damages to property;

[25] "Hurricane Tide Inundation Damage Survey, New York Harbor," prepared by Tippetts-Abbett-McCarthy-Stratton for U. S. Army Engr. Dist., New York, Corps of Engrs., November, 1958.

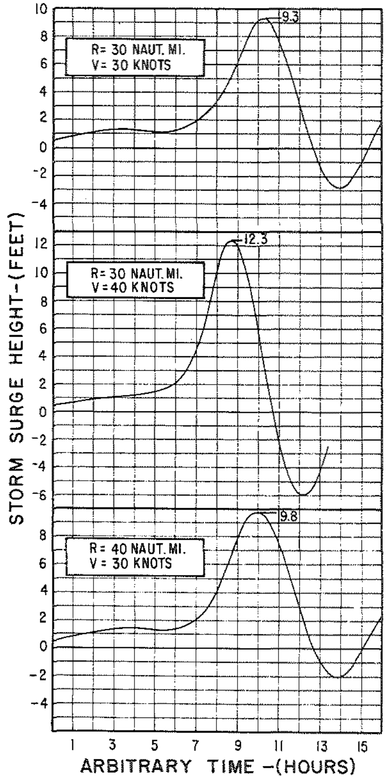

FIG. 10.—PREDICTED STORM SURGE HEIGHTS FOR HURRICANE OF SEPTEMBER 1944, TRANSPOSED

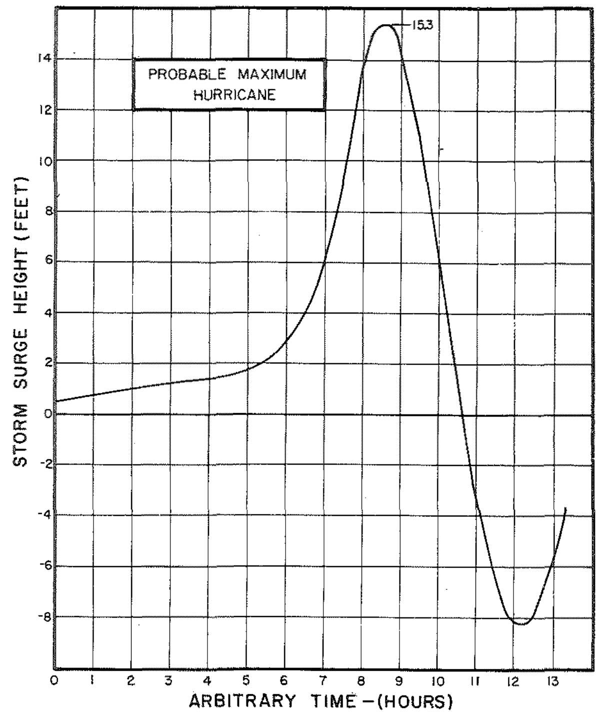

FIG. 11.—MAXIMUM SURGE FROM MAXIMUM POSSIBLE HURRICANE

4. estimates of costs of primary non-physical damages involving the extraordinary costs of emergency services, evacuation, property depreciation, and financial losses, such as loss of income and wages;

5. a general analysis of the secondary effects of inundation on businesses and individuals in and beyond the flooded area, and including such factors as health hazards, evacuation problems, disruption of transport, and effects on industry and commerce; and

6. a brief analysis of existing organizations and procedures designed to cope with natural disasters.

Area Investigated.—The area investigated is the one that would be inundated by a storm tide reaching an elevation of 15 ft above mean sea level, as shown cross hatched in Fig. 12. It embraces 370 miles of tidal frontage in the five boroughs of New York City (with the exception of the Rockaway peninsula in the Borough of Queens), and in Bergen, Essex, Hudson, Middlesex, Passaic, and Union Counties in New Jersey. The Rockaway peninsula was covered by a separate damage survey undertaken as part of the hurricane study of the south shore of Long Island, west of Jones Inlet.

Investigation Findings.

Extent and Value of Inundated Area.—The estimated acreage that would be inundated by a storm tide of 15 ft above mean sea level is 100,900 acres, consisting of 47,500 acres in New York and 53,400 acres in New Jersey. These acreages include marshlands, that in New Jersey constitute about 40% of the total land area inundated in the state. The area inundated in New York comprises 23% of the entire New York City land area, and the area inundated in New Jersey comprises 8% of the total area of the six counties involved. The estimated assessed valuations of the land and of improvements in the inundated areas total approximately four billion dollars. The real valuation is estimated at over five billion dollars.

Population Affected by Inundation.—The total population of the municipalities affected by inundation in New York and New Jersey is about ten million, 80% of which comprises the population of New York City. Of this total, it is estimated that approximately 1,900,000 people would be located in the flooded zones where the land elevation is below the 15-ft level (1,300,000 in New York and 600,000 in New Jersey).

Estimated Primary Damages.—For the entire area, the estimated cost of primary damages that would result from tidal inundation to 15 ft above mean sea level is about five billion dollars (three billion in New York and two billion in New Jersey). Distribution of this cost by categories of damage is shown in Table 9. Distribution of the cost between physical and non-physical damage and by counties is shown in Table 10.

In order to facilitate the analysis and use of the damage estimates, the study area was subdivided into 120 sections (43 in New York and 77 in New Jersey). Separate damage estimates were determined for each section. A brief description of the method used in arriving at the damage estimates, and of the reliability of the estimates, follows.

Method Used in Arriving at Primary Damages.—The primary damage estimates are based on a number of approximations consistent with the broad scope of the appraisal. The estimates were broken down into the following categories: Residential, industrial and commercial, transportation, utilities, public lands and structures, and port facilities. For the determination of residential dam-

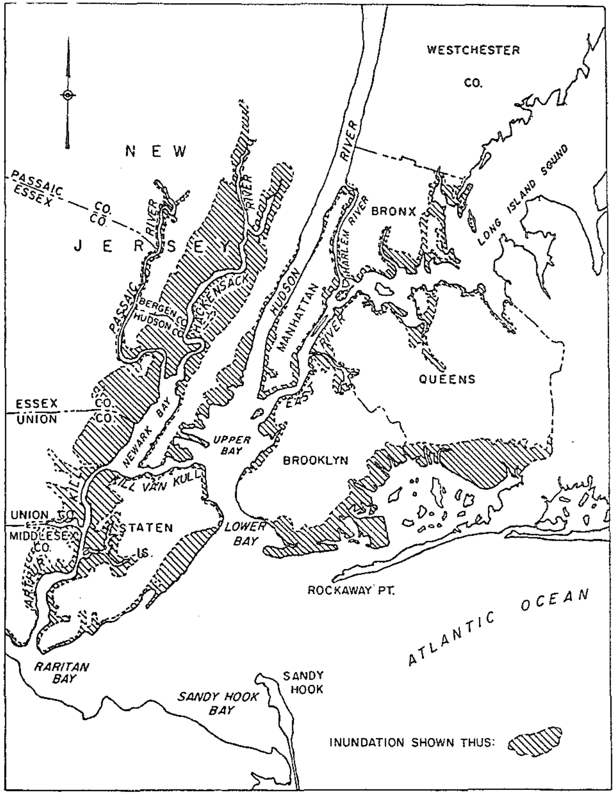

FIG. 12.—AREA INVESTIGATED

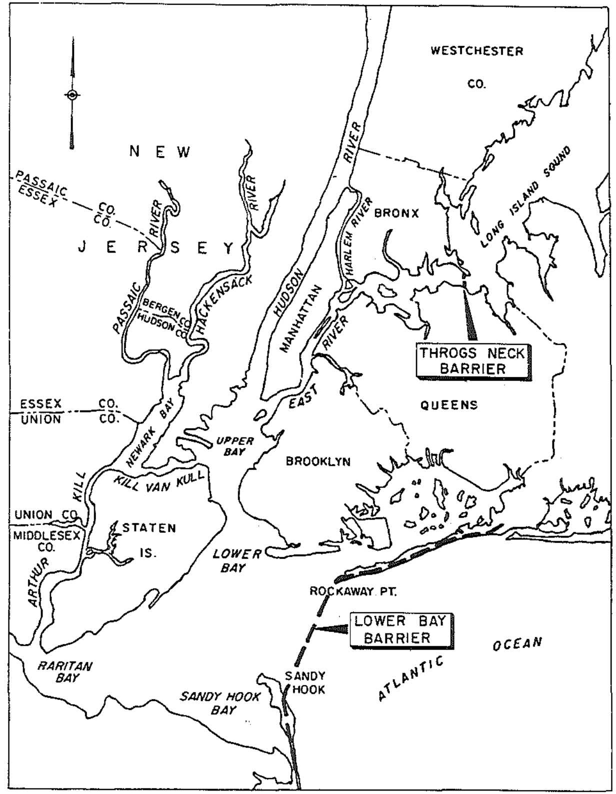

FIG. 13.—PROPOSED BARRIER CONSTRUCTION FOR PROTECTION OF NEW YORK HARBOR

ages, general damage formulas and stage-damage relationships were established for several residential classifications. A field reconnaissance was conducted to determine the number and type of dwellings within the inundated area.

In determining industrial and commercial damages, interviews were conducted with a number of establishments, and the results of these interviews were reduced to a damage per unit area basis for industries and to a damage per front foot basis for retail stores. Areas and front footage were generally measured from land use maps.

Damage to railroads was based on information obtained from some of the principal lines serving the area. This information was used to obtain unit damages that were then applied to all railroad property subject to inundation. Damage to the rapid transit systems was based on information procured from the appropriate authorities.

Each key utility in the area was contacted in order to obtain estimates of damage, as well as estimates of time out of service.

TABLE 9.—ESTIMATED DAMAGES FOR THE ENTIRE AREA BY CATEGORIES OF DAMAGE[a]

Category of Damage (1)	Estimated Direct (Primary Physical) Damages (2)	Estimated Indirect (Primary Non-physical) Damages (3)	Estimated Total Damages (4)
Residential	342,560	62,358	404,918
Transportation	335,157	79,353	414,510
Utilities	48,072	51,849	99,921
Industrial and Commercial	1,561,009	2,117,435	3,678,444
Public Lands and Structures	101,072	4,636	105,708
Port Facilities	144,735	50,000	194,735
Total for All Categories of Damage	2,532,605	2,365,631	4,898,236

[a] In thousands of dollars

Damages included under public lands and structures include Federal, state, and municipal facilities, as well as those of a semi-public nature. Damage data were obtained from the relevant authorities, except for some of the smaller New Jersey municipalities for which unit estimates of other areas were modified to suit the local situation.

Damage to port facilities was determined by tabulating waterfront facilities and then estimating the damages to these facilities and their equipment. In addition, an estimate was made of damage to material in transit.

Secondary Effects of Inundation.—The secondary effects of inundation caused by a hurricane-induced tidal surge of 15 ft above mean sea level in the New York Harbor area would be calamitous. The problem of evacuating people from low-lying areas would have to be resolved in the face of a virtual breakdown of normal transport facilities. Initially, virtually all economic activity in New York City would cease, and a state of emergency would probably be declared. In view of the great concentration in the New York Harbor area of national and

international business and economic activity, the secondary effects of inundation would be felt throughout the United States and in foreign countries.

World and national trade would suffer as a result of the temporary cessation of air, rail, highway, and water transport through New York. Basic industries in the United States and abroad would be affected. Financial activities throughout the world would feel the effects of the temporary closing of the New York Stock and Commodity Exchanges that would possibly result from the curtailment of communication services and electric power supply.

Distribution of food and hospital services and port activities would be severely handicapped for several weeks. The New York City subway system would be inoperative for at least one month, and railroads utilizing tunnels would be affected for weeks.

TABLE 10.—ESTIMATED DAMAGES BY COUNTIES[a]

State and County (1)	Estimated Direct (Primary Physical) Damages (2)	Estimated Indirect (Primary Non-physical) Damages (3)	Estimated Total Damages (4)
(a) NEW YORK			
New York County (Manhattan)	414,026	393,481	807,507
Bronx	120,864	95,965	216,829
Kings County (Brooklyn)	647,383	420,113	1,067,496
Queens	278,892	279,256	558,148
Richmond County (Staten Island)	153,095	134,029	287,124
Totals for New York	1,614,260	1,322,844	2,937,104
(b) NEW JERSEY			
Bergen	182,066	235,004	417,070
Essex	93,189	90,001	183,190
Hudson	412,087	383,620	795,707
Middlesex	107,079	157,311	264,390
Passaic	6,600	9,190	15,790
Union	117,324	167,661	284,985
Totals for New Jersey	918,345	1,042,787	1,961,132
Grand Totals for New York and New Jersey	2,532,605	2,365,631	4,898,236

[a] In thousands of dollars

It is not feasible to place a monetary evaluation on the losses that would result or the additional costs that would be incurred from the aforementioned disruptions to normal activity.

POSSIBLE METHODS OF PROTECTION

General.—Protection against tidal flooding may be practiced in many ways with varying degrees of effectiveness and cost, depending on local terrain con-

ditions and the location and concentration of damages. The methods may be classified under two general categories, those that are preventative and those that are corrective.

Preventative Methods.—The preventative methods may be local or regional in extent. The following are some of these methods:

Hurricane Warning, Evacuation, and Flood Emergency Measures.—Dependable forecasts of the movement of hurricanes by the USWB are necessary if there is to be sufficient advance notice of where and when a hurricane will strike. The forecasts must be supplemented by a specific program of evacuation and flood emergency measures to begin as soon as the early warning is received. Such a program would permit the timely preparations required to protect homes, buildings, goods, and equipment, such as boarding up and sandbagging openings, removing goods and equipment to higher levels or out of the flood area, and evacuating persons to high ground or other areas. However, because the method of forecasting is not foolproof, warnings that are near misses and result in "scares" may not only cause hardships and economic loss, but also may result in reluctance on the part of the affected people to act immediately on later warnings.

Zoning Regulations and Building Codes.--Flood losses may be reduced through appropriate zoning regulations and building code provisions that would limit or control development in flood plain areas. Under this method, development that would be vulnerable to destructive forces of water and waves is not permitted. Some progress has been made by state and local governments in adoption of zoning and building restrictions. On request of local and state governments, the Federal Government, through Section 206 of the Flood Control Act of 1960, is authorized to furnish basic flood data useful in establishing such regulations. However, such measures meet with strong opposition because of their restriction on the growth of an area, with resulting loss in tax revenue to municipalities, and because of the investment in properties that is involved. The flood plain problem has been solved in many cases by the acquisition of these areas by state and local governments for park and recreational use compatible with flood plain zoning.

Corrective Methods.—The aforementioned preventative methods are, of course, limited in effectiveness in highly developed areas. In the localities that have experienced or are subject to severe damage, local or regional corrective measures must be taken for the prevention of such damage. The following are some of the corrective measures that may be undertaken:

Flood Proofing.--This action may be taken by an individual property owner by modifying structures or property in order to minimize flood damage. Measures that may be taken include permanent or temporary closure of openings exposed to floodwaters, installation of valves or gates in pipes to prevent backup of floodwaters, installation of pumps to control seepage, and construction of ring levees or walls to hold back floodwaters. These measures tend to be uneconomical when compared with local protection works that protect more than one unit. In many cases, the structures used are not designed with an appropriate factor of safety against water pressures, overtopping, seepage, sliding, and uplift. The measures may interfere with the efficient use of space, with a resulting reduction in, or increased cost of, productivity.

Local Protection.--This consists of work of a localized nature intended to protect a large number of concentrated properties in a flooded area in which damages are sufficiently concentrated to warrant such protection. Such im-

provements are usually constructed by the community or by the local and Federal governments. Examples of local protection works that have been found effective are as follows:

1. Walls, Levees, and Interior Drainage Facilities: This type of improvement protects a flood area by the use of structures that are built along a river or shore front and tied into high ground, and that hold back floodwaters and provide for the surface drainage trapped within the works. The height of these structures must be carefully determined, for if they are too low, they will give a false sense of security and encourage development of low-lying areas. Overtopping of the protective works may result in considerable damage and possible loss of life.

2. Restored Beaches, Dunes, Earth Dikes, and Interior Drainage Facilities: Along the exposed sandy coastline, where beach erosion is involved, this type of improvement has been found suitable for protection against hurricane floods with attending wave action. However, one of the principal objections to such protection is the blocking of both the view and access to the beach that results from the high structures required for prevention of tidal inundation during major storms, especially in highly developed areas. Such measures have been authorized for the south shore of Long Island between Fire Island Inlet and Montauk Point[6] and are being considered for other coastal areas.

3. Low Walls and Bulkheads: Such structures are usually constructed by individual property owners to provide protection against erosion and to reduce wave action. Because the structures are too low to prevent inundation by extreme high tides, they may create a false sense of security with attendant risks.

4. Breakwaters: In exposed coastal areas, these structures break up wave action and reduce damage to coastal properties and small craft. Generally, they have little effect on water levels and are ineffective in reducing tidal flooding.

5. Barriers: Topography at the mouths of rivers, estuaries, and bays may be suitable for construction of barriers or dams, with or without gated openings, to keep the storm tidal surges out of the area of protection. Walls or dikes are sometimes required to tie the structures to high ground. Such barriers have been authorized in Narragansett Bay for the protection of Providence, R. I., and, also at New Bedford, Mass.

Consideration has been given to the construction of barriers at the entrance of Lower New York Bay and at the western end of Long Island Sound for the protection of New York Harbor, as shown in Fig. 13. Such a structure at the entrance of Lower New York Bay would extend approximately 7 miles across the bay and would require approximately 15 miles of walls or dikes along Sandy Hook and Rockaway peninsula in order to tie in with high ground. The maximum height of the barrier would be approximately 70 ft, extending from approximately 45 ft below mean low water to 20 ft above mean sea level. A required navigation opening would be 2,000 ft along Ambrose Channel and 800 ft along Sandy Hook Channel. The barrier at the entrance from Long Island Sound at Throgs Neck would involve a basic length of 4,000 ft and a maximum height of approximately 100 ft, from a depth of over 75 ft below mean low water to 25 ft above mean sea level. This structure would require a 1,000-ft navigation opening. Aside from the difficulties of construction and high cost, protection by the barriers has been strongly opposed because of navigation difficulties and pol-

lution considerations. Such structures would also require consideration from the standpoint of national defense.

Conclusion.--The New York Harbor hurricane study has not progressed to the point at which it might be possible to select any particular method of protection. It is expected that a suitable plan of protection would involve a combination of most of the methods examined, depending on the local conditions.

COOPERATION BETWEEN FEDERAL, STATE, MUNICIPAL, AND OTHER INTERESTS

Public Hearings.—After assignment of the hurricane study of the New York Harbor area to the New York District, Corps of Engineers, a public hearing was held in New York City by the District Engineer in January, 1956, covering the five boroughs of the city. In February, 1956, a similar public hearing was held in Newark, N. J., covering the New Jersey streams within New York Harbor. Other Federal, state, and municipal agencies and interested parties were notified of the hearings and requested to furnish information on improvements desired. With the exception of requests for protection of some of the coastal areas by means of groins, bulkheads, levees, and the use of hydraulic fill to raise low areas, the majority of local interests expressed a desire for general improvement, but without specifying the type of protective structures.

Orientation Meeting.—After completion of the hurricane research and the appraisal of the hurricane damage and hazard in the New York Harbor area, with the assistance of many individuals, companies, and governmental and private agencies, the District Engineer invited all interested Federal, state, and New York City agencies to attend an orientation meeting in September, 1959. At this meeting, the hurricane problem and possible remedial measures for protection against severe tidal inundation, including hurricane barriers, were discussed, and each agency was requested to submit written comments. In view of the many interests involved, it was suggested that a committee be formed by the states of New York and New Jersey and the City of New York to act as a coordinating body between the Corps of Engineers and local agencies in regard to matters dealing with the hurricane study of New York Harbor.

New York Harbor Study Coordinating Committee.—In accordance with the suggestion made at the orientation meeting, a New York Harbor Study Coordinating Committee was formed, consisting of the District Engineer, New York District, Corps of Engineers; the Commissioner, Department of Conservation and Economic Development, State of New Jersey; the Director of Port Development, Port of New York Authority; the District Engineer, District 10 of the New York State Department of Public Works; the Chief Engineer of the New York City Board of Estimate; and a respresentative of the New York City Construction Coordinator.

A meeting of the coordinating committee was held in March, 1960. At this meeting a summary was presented of the comments received from the various agencies after the orientation meeting. Several of the comments pointed to the need for an adequate preparedness plan to cope with the hurricane disaster, and some favored consideration of flood plain zoning and revision of building codes. One suggestion was made for the use of the New York Harbor model at the Waterways Experiment Station, Vicksburg, Miss., to complement work done in developing a preparedness plan. A number of suggestions were made

to consider local protective works. The comments showed a general lack of support for construction of hurricane barriers at the entrances to New York Harbor on the basis of the following reasons: (1) Questionable feasibility; (2) extreme high cost and unlikelihood of economic justification; and (3) the possibility of water pollution.

The scope of the New York Harbor hurricane study was examined. It was noted that the report would outline the nature of hurricane problems; the types of direct solutions that might be provided; corrective actions that might be undertaken locally, such as zoning and adoption of improved building codes; and hurricane preparedness and evacuation problems. The report would also delineate the areas that might warrant further detailed study in the development of plans for local protection works. As of 1962, the only sections within the New York Harbor area where such works are being studied in detail are the east shore of Staten Island, from Arthur Kill to Fort Wadsworth, and the Atlantic Coast of New York City, from East Rockaway Inlet to Norton Point, including the Rockaway and Coney Island areas. The hurricane study will be combined with cooperative beach erosion control studies of the same areas.

The coordinating committee proposed that the hurricane study report on New York Harbor include appendixes on hurricane warning, preparedness and evacuation plans, and revision of zoning regulations and building codes, and it suggested that these appendixes be prepared by respective subcommittees.

CONCLUSIONS

The results of the hurricane studies of the New York Harbor area that are completed to date (January 1, 1962) disclose that this area is vulnerable to great potential damage from tidal inundation that may disrupt all economic activity in this largest harbor and metropolitan area in the world. Secondary effects from possible inundation to 15 ft above mean sea level would be felt throughout the United States and in foreign countries.

In connection with a preliminary investigation of possible methods of protection, local interests showed a lack of support for hurricane barriers at the entrances to New York Harbor; consequently, this type of improvement cannot be successfully pursued. Desired improvements consist of local protective works, an adequate preparedness plan to cope with the hurricane disaster, flood plain zoning, and revision of building codes.

Under the present scope (January 1, 1962) of the New York Harbor hurricane study, the report will delineate the areas that may warrant protective works. It will include recommendations for corrective action that may be undertaken locally. To this end, local subcommittees are working towards improving the hurricane warning system, establishing preparedness and evacuation plans, and revising zoning regulations and building codes.

ACKNOWLEDGMENTS

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eral, state, and municipal authorities and private interests, assisted in the damage appraisal. The writers acknowledge the leadership and direction of Charles M. Duke, F. ASCE, Thomas DeF. Rogers, and John T. O'Neill, who served as U. S. Army District Engineers, and the technical guidance of Charles K. Panish, F. ASCE, Chief of the Engineering Division of the New York District. They also acknowledge the assistance in the research work of the following District personnel: Morris Colen, Herbert Howard, A. M. ASCE, Milton K. Schneider, Daniel C. Malcolm, and Horace B. Miles. The clerical assistance of Mrs. Ray Goodfield is appreciated. The approval of the Office of the Chief of Engineers to publish this paper is also greatly appreciated.

DISCUSSION

D. M. THOMAS,[26] A. M. ASCE.—The description of the United States Corps of Engineers tidal flood evaluation study of New York Harbor is of interest. The sections on the detailed and intensive historic data analyses, and on the analytical prediction of probable maximum hurricane tides, are particularly enlightening.

The storm-tide frequency relationships developed from gage records and presented in Figs. 6, 7, and 8 are indicated as useful for study of economic justifications of remedial measures, and are also used to evaluate tide elevations of transposed hurricanes. Presumably, the relationships of Figs. 6, 7, and 8 are considered directly applicable to nearby on-shore areas.

Data obtained after the "Great Atlantic Coast Storm" of March 6-7, 1962, and also in a study of tidal floods at Atlantic City, N. J., and vicinity[27] show impressive differences between maximum storm-tide elevations determined at on-shore points and corresponding maximum elevations at nearby tide gages. Maximum elevations (above sea level datum of 1929) for the March, 1962, tide at the Sand Hook, N. J., Atlantic City, and Lewes, Del., tide gages were 7.3 ft, and 7.9 ft, respectively. On-shore elevations determined to date (July, 1962) along the New Jersey oceanfront between Sandy Hook and Lewes varied from 8.6 ft to 12.1 ft and averaged 10.6 ft. Similarly, for the September 14, 1944, storm tide at Atlantic City, an elevation of 7.6 ft was determined at the tide gage, and on-shore elevations within 3 miles of the gage varied from 10.0 ft to 12.0 ft. The maximum on-shore elevations were determined from either a single high-water mark judged by visual inspection as representative of the area or by averaging the elevations of high-water marks in the area.

On-shore and gage elevation differences were previously noted in Report No. 7 of the National Hurricane Research Project.[14] In this report, the elevation differences were attributed primarily to the small lateral extent of hurricane-produced extreme tides and the correspondingly small chance that an extreme tide would occur at a gage site. However, data from the Atlantic

26 Hydr. Engr., U. S. Geol. Survey, Trenton, N. J.

27 "Tidal Floods, Atlantic City and Vicinity, New Jersey," by D. M. Thomas and G. W. Edelen, Jr., Hydrol. Inv. Atlas 65., U. S. Geol. Survey, Washington, D. C., in preparation.

City tidal flood study indicate that there may be a consistent areal pattern of variation of maximum on-shore elevations. For example, at the Atlantic City tide gage, which is located approximately 1,500 ft offshore, the elevation of the hurricane storm tide of 1944 was 7.6 ft, and the elevation of the extratropical storm-tide of 1962 was 7.2 ft. Directly shoreward from the gage in an area sheltered from the open sea by sand dunes and the boardwalk, the on-shore elevations for 1944 and 1962 were 10.0 ft and 8.6 ft, respectively. Approximately 3 miles southward along the shore from the gage, the maximum on-shore elevations for 1944 and 1962 were 12.0 ft and 10.8 ft, respectively. Available data, however, are insufficient to explain the reasons for the areal pattern of elevation difference.

Because high-water marks are believed to be the best indicators of on-shore maximum water-surface elevations, and becuase the water-surface elevations determined from high-water marks may vary in an areal pattern that differs significantly from corresponding tide gage elevations, it is suggested that an investigation of on-shore and gage elevation differences would be a worthwhile addition to tidal flood studies.

A point of perhaps academic interest concerns the selection of a 15-ft tide elevation for appraisal of storm-tide damage. If the 15.3-ft surge (as shown in Fig. 11) for a maximum probable hurricane occurred at time of high astronomical tide, an elevation of 18 ft or more might be possible. It is agreed, however, that the effects of such a rare tide, whether of 15-ft or 18-ft elevation, would be calamitous.

BASIL W. WILSON,[28] F. ASCE.—As one who participated in some of the research[16,29,30] connected with storm tide effects on New York Bay, the writer is particularly interested in the authors' review of the over-all problem. It would seem that in deciding on a standard for the appraisal of potential hurricane damage and hazard the authors were, to some extent, influenced by the writer's finding of 15 ft as the ultimate storm surge height for the maximum possible hurricane. However, they have obviously decided to consider this height as the composite of storm flood and normal astronomical high tide. Their standard, therefore, is nearly the equivalent of the 1821 hurricane surge taken in phase with high tide. If high tide were added to the writer's ultimate storm tide, the highest possible water level would be of the order of 18 ft above mean sea level.

The authors' examination of storm frequencies leads to the query as to what the justifiable cost might be of construction measures to minimize the hazards of storm damage to New York and its environs. The writer suggests a possible quantitative estimate, even though facts and figures available to him are quite flimsy.

It seems plausible that the dollar value, D, of storm damage will be a power function of the storm tide height H (inclusive of astronomical tide). If the appraisal that $D \simeq 5$ billion dollars for $H = 15$ ft and the fact that $D > 20$ million

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[28] Senior Staff, National Engineering Science Co., Pasadena, Calif.

[29] "Hurricane Tide Prediction for New York Bay," by Basil W. Wilson, Proceedings, 7th Coastal Engrg. Conf., Hague, Netherlands, August, 1960, Council Wave Research, Berkeley, Calif., April, 1961, pp. 548-584.

[30] Discussion of "Prediction of Hurricane Storm Tides in New York Bay," Tech. Memo No. 120-A, Beach Erosion Bd., Corps of Engrs., U. S. Dept. of the Army, April, 1961.

TABLE 11.—EXPECTED DOLLAR VALUE OF STORM DAMAGE IN A PERIOD OF 100 YR

Surge height above MSL, H, in feet	Number of occurrences in 100 yr, m	Dollar value of damage (single storm), D, in 10^6 dollars	Total value of damage, mD, in 10^6 dollars
15		5000	
8	3	17.4	52.2
6	20	14.3	286.0
5	80	2.5	200.0
		Total	538.2

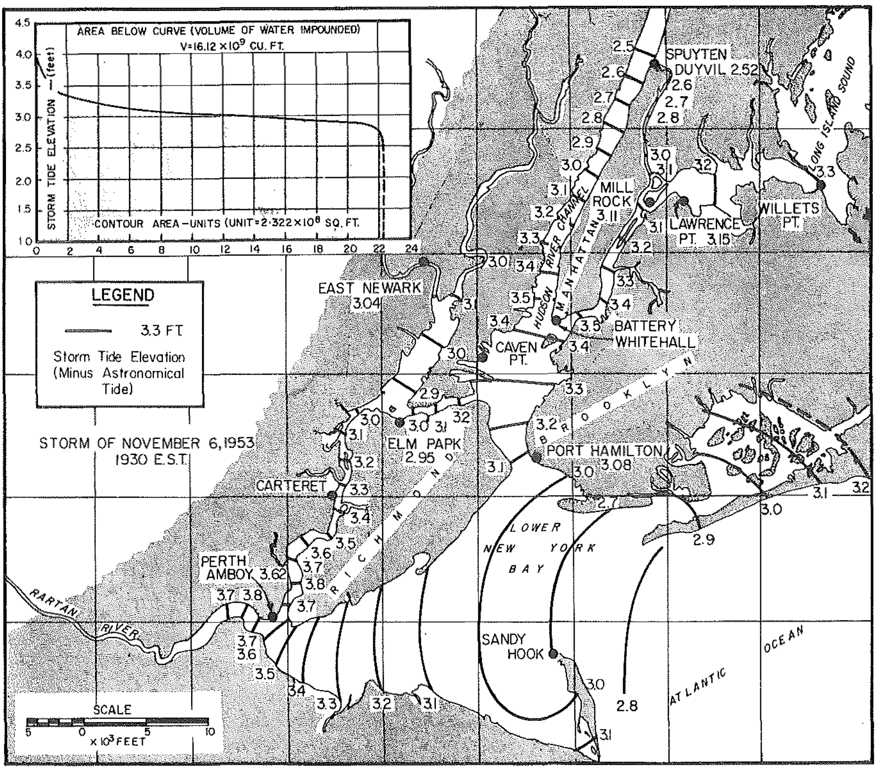

FIG. 14.—TYPICAL SAMPLE OF CONTOURED STORM-TIDE HEIGHTS (MINUS ASTRONOMICAL TIDE) IN NEW YORK BAY AT 1930 EST, NOVEMBER 6, 1953

dollars for H = 8.4 ft, as caused by hurricane "Donna" in 1960, is accepted, then a law

$$D \propto H^9 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

may reasonably be inferred. For "Donna" this relation would give D = 26.5 million dollars.

From the authors' results in Fig. 6, it may be assumed that in a period of 100 yr, there will occur three storms of height $H \simeq 8$ ft, twenty storms of height $H \simeq 6$ ft, and eighty storms of height $H \simeq 5$ ft. The dollar extent of total damage will then be in accord with Table 11. From Table 11 it seems reasonable to infer that the average damage losses per year (on a 100-yr basis) will be approximately $5.4 million.

The next question that may be posed is what capital cost of structures or measures, to minimize this loss, would be justifiable. In order to obtain a quantitative answer, it will be assumed that the measures contemplated will be only 80% effective in shaving the average annual loss by $4 million, leaving an annual average residual burden of $1.4 million. In order to be economical, the structures, having a first capital cost of N dollars, would then be required to show a justifiable annual cost of $4 million.

If the structures should take the form of barriers and dykes, it may be assumed that depreciation, involving maintenance, will reduce their value by 20% in a period of, for example, n (=25) yr. Accordingly, if r% is the interest rate of amortization, the actuarial first cost, N, will be given by the equation:

$$r\,N\left[1 + \frac{0.2}{(1+r)^n - 1}\right] = 4 \times 10^6 \quad \ldots\ldots\ldots \quad (2)$$

For r = 4%, Eq. 2 shows that N could justifiably be approximately $100 million. This value probably could be upgraded considerably because increasing development of New York with passage of time will probably increase the potential for storm damage and amend Eq. 1. Apart from this, if a storm of flood height H greater than 8 ft should occur within a 100-yr span, the justifiable first cost could easily be greater, within the billion dollar range.

Of the possible solutions that the authors have mentioned for storm flood problem, only barrier and dyke or levee systems are apt to avail. Of these, it would seem that only the proposed Sandy Hook-Rockaway Point barrier, in conjunction with a barrier at Throgs Neck, Long Island Sound, could be effective in reducing the flooding. A typical flood condition in New York Bay, existing at 1930 EST on November 6, 1953, during the extratropical storm listed in Table 6, is shown in Fig. 14.[16] It is to be noticed that the flood height of 2.8 ft at the bay mouth has been augmented to 3.8 ft near Perth Amboy and 3.5 ft near the Battery by the funnelling effects of the Raritan River estuary and the lower Hudson River reaches. Fig. 15,[16] which depicts the storm-tide elevations, flood conditions at the bay mount, and the total volume of flood water impounded within New York Bay and its river reaches, for this 1953 storm and also the hurricane of September 14, 1944, shows that at 1930 EST, November 6, 1953, the inflow was quite leisurely (approximately 0.35×10^6 cfs at an average velocity of approximately 1 ft per sec). By 2200 EST, the in-

flow rate had more than trebled and, although for 2 hr thereafter the inflow rate fell off, the total volume of water impounded in the bay increased steadily.

Assuming for this case that the Sandy Hook-Rockaway Point barrier were in existence with a restricted entrance only 2,800 ft wide, the over-all situation might not be too different, as an enhanced rate of influx would merely compensate for the constriction.

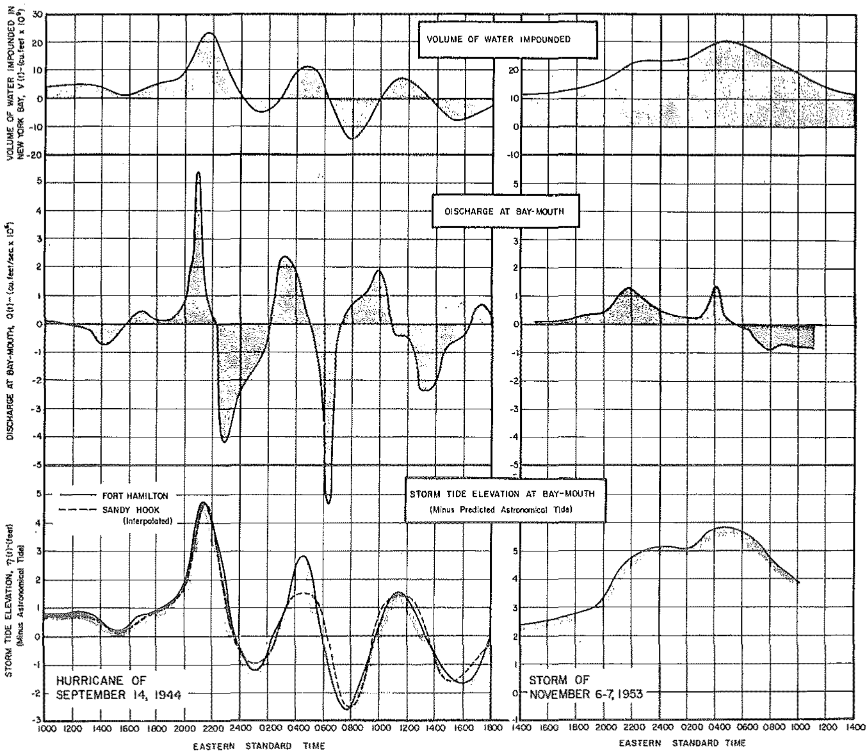

FIG. 15.—VOLUME OF FLOOD WATER IMPOUNDED AND BAY-MOUTH DISCHARGE COMPARED WITH STORM-TIDE ELEVATION AT THE MOUTH OF NEW YORK BAY, FOR (LEFT) HURRICANE OF SEPTEMBER 14-15, 1944; (RIGHT) STORM OF NOVEMBER 6-7, 1953

In the case of a hurricane such as that of September 14, 1944, Fig. 15 shows that the maximum inflow at the bay mouth attendant on the first surge was 5.4×10^6 cfs at approximately 2100 EST (velocity approximately 14.3 ft per sec). Assuming the barrier to be in existence and an enhanced inflow resulting from the constriction, the degree of flooding would depend greatly on the extent to which the over-all inward discharge had been reduced to the time of ebb following the first surge. The problem is a delicate one that would require careful analysis to assure that the benefits of reduced flooding could

give economic justification to the construction of the barriers. It must be realized, in addition, that in the case of hurricane resurgences the barrier could be a distinct disadvantage because it would reduce the rate at which the bay could clear itself of impounded water before the next surge commenced to add water again to that already entrained.

There is an alternative solution to the problem, which the writer ventures to advance regardless of the many practical problems and political and local

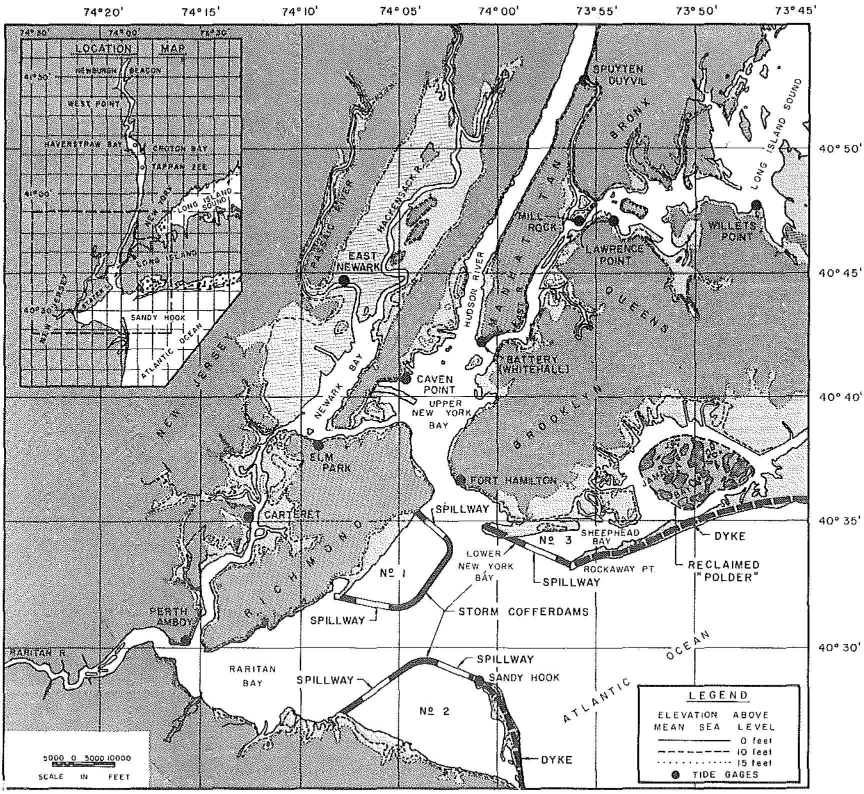

FIG. 16.—MAP OF NEW YORK BAY AND RIVER SYSTEM SHOWING SUGGESTED STORM COFFERDAMS FOR CONTROL OF FLOODING

oppositions that might otherwise tend to rule it out of court. The solution would be extremely costly, but could possibly be justified economically on the basis of earlier discussion. Shown in Fig. 16, the scheme envisions the creation of three large "storm cofferdams" with spillways and controlling gates that might be patterned on the flood control gates now being constructed by Dutch engineers at the mouth of the river Scheldt. The cofferdams would function somewhat as the pores of a sponge to absorb some of the storm flood that would

otherwise permeate throughout the riverine network of New York and New Jersey. The cofferdams would also partially restrict and choke off the flow by creating new entrance channels to Raritan Bay and Lower New York Bay near Fort Hamilton without affecting shipping or normal drainage and circulation in the bay.

Referring again to the situation of Fig. 14 with the supposition that the storm cofferdams were now in existence, the flooding would be kept under control by drawing off water via the five large spillways into the three receiving reservoirs within the ambit of the cofferdams and their auxiliary dykes or levees. No. 1 storm cofferdam would comprise part of Lower New York Bay and be rooted to Richmond, there encompassing low-lying land, now prone to be flooded. No. 2 cofferdam would entrain an area of the bay in the lee of the Sandy Hook spur, backed by coast which is now also prone to be flooded. Finally, No. 3 cofferdam would seal off Sheepshead Bay and most of Jamaica Bay behind Rockaway peninsula. The numerous islands of Jamaica Bay could be fused with dredged material to form a large "polder" of reclaimed land and thus provide New York with increased land acreage for new development. A large area of indented coast, forming part of Brooklyn and Queens, much subject to flooding, would automatically be protected.

The total surface area of the three storm cofferdams would approximate 1.5×10^9 sq ft. Assuming that they were dredged or excavated to a uniform depth of 40 ft below spillway level, their total capacity for impounding floodwater would be 6×10^{10} cu ft, which would be more than adequate to absorb the floodwaters from such storms as the 1944 hurricane or the 1953 extratropical storm (see Fig. 15).

The storm cofferdams would have to be equipped with powerful pumping equipment for emptying the reservoirs whenever the floods receded. In the case of a hurricane, the degree of emptying after the main surge need only be partial to the time of the first resurgence, provided the over-all storage capacity of the three cofferdams were adequate to handle repeated floodings, as seems probable for the figures that have been quoted.

The sill levels and breadth of the spillways, and their floodgate controls, would have to be carefully investigated to assure the optimum protection for the upper reaches of New York and Newark Bays. By suitable design of the system suggested, the writer believes that New York's flood damage problem could be almost entirely relieved and that the cost of the necessary protection, moreover, could probably be economically justified. It is altogether another question whether the opposition of fishing and coastal interests that would be affected by the storm cofferdams could successfully be overcome. However, there are certain compensations that could possibly overshadow the deprivations and inconveniences to coastal communities affected by the building of the cofferdams. For instance, there seems no reason why small yacht and fishing harbors should not be built on the seaward side of the storm cofferdams, clear of the spillways, and that easy access to them could not be made by highways along the summits of the breastworks. Furthermore, the reservoir areas could be allowed to retain a small quantity of water at all times to permit the development of the enclosures as recreational parks for boating and water sports. Elbows of the storm cofferdams could be broadened to provide shade trees and picnic areas above storm flood level. Finally, the great lengths of almost straight dykes could conceivably be developed as broad land-runways for the supersonic passenger aircraft of the future.

Nothing has been noted herein concerning control of the flooding from Long Island Sound. A similar system could probably be devised for this area but, as the floods are naturally retarded by the greater constrictions of the channels west of Willets Point, partial barriers may be the simplest and most effective deterrent to serious flooding.

SAMUEL GOFSEYEFF[31] and FRANK L. PANUZIO,[32] F. ASCE.—The writers were especially interested in the discussions submitted by Wilson and Thomas based on their familiarity and past experience with tidal problems.

Wilson's participation in the original studies of tidal surges in New York Harbor form the basis of analysis of the hurricane problem in New York Harbor. Wilson's suggested Eq. 1 for determining damage from tidal inundation based on the estimated damage in the New York Harbor area from hurricane "Donna" and from an assumed tide of 15 ft above mean sea level may be adequate for a rough approximation, but would not afford a firm basis for economic analysis of an improvement due to nonuniform variation of land area and development with depth. In general, damage stage relations are not susceptible to expression as a simple formula. However, having determined the average annual damage, the justifiable capital cost of improvements may be expressed in a formula similar to the suggested Eq. 2 by using proper values for residual damage, rates of interest, and depreciation and maintenance costs.

Wilson's suggested alternative solution to the proposed Sandy Hook-Rockaway Point barrier consisting of three large "storm cofferdams" with spillways at the mouth of the harbor is intriguing and warrants consideration, but it poses not only possible political and local opposition but also engineering problems as well as cost considerations that may not be commensurate with reduction of damages. It is worthy to note that a barrier plan for Jamaica Bay similar to the one noted by Wilson is under study as a possible solution to the Rockaway and Jamaica Bay flooding problem.

Thomas' suggestion for an investigation of on-shore and gage elevation differences is timely and worth pursuing. In reviewing the storm tide elevations at tide gages and from high water marks of all hurricanes and major extratropical storms since September 1938 in the New York District area, the on-shore elevations obtained from high water marks were generally found to be greater than those recorded by tide gages. Although some of the differences may be attributed to the effect of wave run-up, some may be due to the areal pattern of variation described by Thomas.

31 Chf., Beach Erosion and Hurricane Reports Sect., Corps of Engrs., U. S. Army Engr. Dist., New York, N. Y.

32 Asst. Chf. for Civ. Works, Engrg. Div., Corps of Engrs., U. S. Army Engr. Dist., New York, N. Y.

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